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IOP Publishing Environ. Res. Lett. 15 (2020) 114007 https://doi.org/10.1088/1748-9326/abb9dc

Environmental Research Letters

OPEN ACCESS

RECEIVED
21 April 2020

REVISED
28 August 2020

ACCEPTED FOR PUBLICATION
18 September 2020

PUBLISHED
14 October 2020

LETTER

How urbanization enhanced exposure to climate risks in the Pacific: A case study in the Republic of Palau

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Keywords: urbanization, climate change, risk, coastal flooding, water shortage, Pacific islands

Abstract

The increasing risk of coastal flooding and water shortage in Pacific Island Countries is usually attributed to climate change hazards. This ignores other risk components, exposure and vulnerability, of which a major contributor is urbanization.

We develop simplified analyses that can be applied to other PICs. By dividing climate risks into hazard and exposure components we determine how urbanization contributed to present-day risks and then predict how growing climate change hazards may increase future risk, using the Republic of Palau as a case study.

Results show that urbanization was responsible for 94% of the buildings exposed to coastal flooding today. Projected sea level rise, 30.2 cm by 2050, only increased exposure of today's buildings by 0.5%. In both present and future scenarios exposure resultant from urbanization was more significant than sea level rise.

Our water scarcity index showed urbanization caused 3 of the 7 recorded water shortages from 1980–2018. From 2041–2079, analysis of projected rainfall showed mean reductions between 1.6–16.6% and increased variance between 0.3–3.4%. This led to three times as many water shortages under present population levels. In historical and future scenarios exposure from increased population was just as significant in causing water shortages as rainfall variation.

These findings suggest that urban management is an important tool to lower exposure to coastal flooding and water shortage and we recommend that decision makers prioritize urbanization within climate risk policy in Pacific Island Countries.

1. Introduction

The IPCC recognizes climate change-induced sea level rise and changing rainfall patterns as 'key climate and ocean drivers of change' in island nations (Nicholls *et al* 2007, Parry *et al* 2007, Nurse *et al* 2014, IPCC 2019). These synergistic hazards pose a particularly high threat to exposed Pacific Islands Countries (PICs) characterized by their high coastline to land mass ratio (ADB 2013; Church *et al* 2006, Kumar and Taylor 2015). Coastline and precipitation conditions worsen at higher rates in PICs as atmospheric warming fuels sea level rise and El Niño frequency affecting both short- and long-term hazards at unprecedented rates (Church *et al* 2006; Becker *et al* 2012, Nurse *et al* 2014; Chand *et al* 2017, Power *et al* 2017; Wang *et al* 2017, Nerem *et al* 2018). These hazards are *very likely* to continue growing in the future (IPCC 2019) and PICs remain on the front line of rapidly growing hazards.

It is important to note here that sea level rise and changing rainfall patterns are not risks themselves, but hazards affecting the risk of coastal flooding and water shortage, respectively. Since risk is defined as a function of hazard (natural weather or geological events), exposure (how likely one is to be affected by hazards) and vulnerability (one's inability to cope with exposure to hazards) a complete risk assessment requires the analysis of socio-geographic factors like urbanization, as well (ADRC 2009).

Urbanization flourished in PICs after WWII, due to migration from rural areas to government and economic centers (ADB 2013, Connell 2015). These centers were often chosen by colonial powers for their deep ports or general access to the sea, meaning they are often located in flood prone areas (ADB 2013). Therefore, to understand risk in the Pacific it is necessary to understand how urbanization in these areas contributed to increases in coastal flooding and water shortage risk.

Nevertheless, urbanization is often overlooked in PICs' risk studies, though it is a known contributor to risk that increases exposure and vulnerability to coastal flooding and water shortage (ADB 2013, UNIDSR 2015). Studies in other regions of the world found the combined effects of urbanization and climate change to non-linearly increase risk (Pumo *et al* 2017, Sofia *et al* 2017; Sebestian *et al* 2019). While Kumar and Taylor (2015) examine proximity of vital infrastructure to coastlines over several PICs, data insufficiency limits the ability of researchers to perform the same combined effects studies that quantify changes to exposure in PICs. This research investigates that gap using unique methods to overcome data availability issues. If exposure has significant impacts on risk in PICs it means that urban management can potentially act as an adaptation method to increasing climate change hazards.

2. Methodology

2.1. Case study: Republic of Palau

Urbanization research in PICs is scarce due to the sheer diversity of island lithology, varied economies (e.g. tourism, aquaculture, administrative center), and difficulty in gathering data related to urbanization such as historical maps and population changes. Palau, however, has gathered and preserved urbanization and meteorological data since the 1950s. It has more land and water resources than atoll PICs potentially enabling it to be more resilient to climate change (e.g. Forbes *et al* 2013). Even its corals appear to be more resistant to ocean acidification caused by climate change (Barkley *et al* 2017). As Palau has potential to withstand higher levels of climate change hazards, urbanization exposure becomes even more important to manage to adequately suppress climate risk.

Palau sits in the Western Pacific composed of 16 local state governments spread over more than 300 volcanic and limestone islands and sand atolls. Nine of these states are located on the largest island, Babeldaob (figure 1), but most residents (65%) live in the urban center of Koror (ROP 2015). Koror's population has grown from 658 people in 1946 to 11 444 in 2015 (Republic of Palau (ROP) 2015). When grouped with its neighboring state, Airai, which holds the sole water source for the two states, they form Palau's formal urban area (Republic of Palau (ROP) 2015). Palau has one of the highest urbanization rates in the Pacific, with 78% of the population residing in the urban area (ADB 2016).

Koror's livable area is composed of three islands: Koror, Ngarkebesang and Malakal, which are connected by causeways. The peaks of these islands reach over 120 meters above sea level (MASL). Development in these steep areas is low because of the cost and difficulty of constructing buildings and roads. Main Street acts as the spine of the urban center and reaches an elevation of 50 MASL in eastern Koror. It follows a ridge through the downtown area at roughly 20 MASL. Development is generally located downhill from Main Street towards the mangroves.

The population growth coupled with limited development space has forced Koror State to lease out areas inhabited by mangroves and reefs, on which new residents clear, infill and build homes. These mangroves occur adjacent to both the coast and close to mean sea level (Woodroffe and Horton 2005), thus properties built in their place are exposed to flooding that can occur during high tides and storms/typhoons. Population growth has also increased demand on fresh water and particularly the primary shared water source, the Ngerimel Dam. When water shortages occur, the National Government and local utilities company implement water-usage hours as extreme as 1 h per day.

2.2. Urbanization data

2.2.1. Spatial data

To prepare Koror's spatial data for coastal flooding risk analysis, we take historical maps and modern GIS data from Palau's national GIS office (PALARIS 2018). We post-process two United States Geological Survey (USGS) maps from 1954 and 1983, both 1:25 000 scale (USGS) by geo-referencing them in ArcMap 10.1 and delineating the buildings (note the 1954 map does not show full coverage of Koror, see figure 5 for map extent).

In 1954, Koror had 195 buildings (see figure 5). By 1983, Koror had 1576 buildings (see figure 5). This is equivalent to almost four new buildings every month though the population had yet to reach 10 000 people. Buildings also moved closer to the coastline and even into the mangroves.

Expansion continued and by 2018 Koror had 3219 buildings (see figure 5). As most land on flatter, more easily developable grounds were taken, new developments were forced into mangroves and low-lying areas. Faced with continued growth and land ownership issues that made inland development even more difficult, Koror continues to alleviate development pressures through coastal development, further increasing coastal flooding risk.

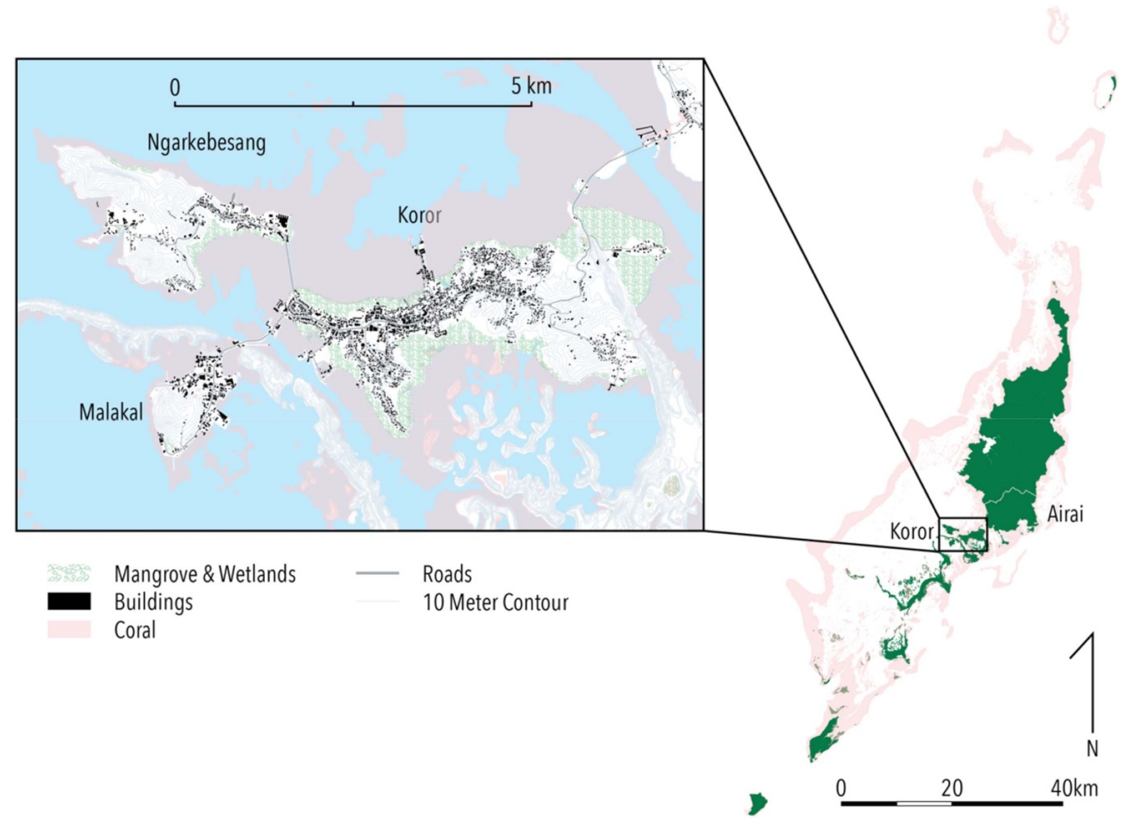

Figure 1. Map of Palau (not including Southwest Islands) and detailed map of Koror.

2.2.2. Population data

Population data was used to analyze water shortage risk. Censuses from 1980 to 2015 provided the number of households attached to the public water system. These were multiplied by the average number of people per household to get the number of public water users in the urban area. In the absence of more detailed population data we assume a linear growth or decline between all actual Census counts to estimate monthly data.

Government data also provided tourist arrivals from 1980 through 2018 and the current number of hotels rooms (PVA 2019). After June 2007, tourist arrivals are reported by month. Before that, however, annual tourist arrivals are the most detailed data available. To estimate monthly data before June 2007, the average annual share of tourists for each month after June 2007 were calculated and the resulting ratio used to make monthly tourist arrival estimates for past years. Monthly tourist arrivals were then converted to a population equivalent using tourist nights while years without tourist night data used an average of the data that was available. Finally, we assumed equal occupancy rates across all hotel rooms in Palau then multiply the proportion of rooms in the urban area (91.6%) by the tourist population equivalent. This likely makes the tourists portion of the population an underestimate as not only are most accommodations in the urban area, but an even greater proportion of tourists related facilities like restaurants, shops.

While population growth increased over the analysis period, the number of public water users grew even more as the number of households connected to the public system increased from 70% to over 95% (see figure 2). After 2000, the number of connected households stabilizes and sees only minor growth to 97% in 2015. Tourism data exhibited two high seasons, one in January to February and the other from July to August. Annual visitors fluctuated year to year, with the highest mark reaching over 163 000 in 2015, but generally showed continuing upward trends in growth.

2.3. Climate data

2.3.1. Extreme events and long term sea level

Palau has a tide gauge (Malakal-B) located in Malakal, which spans from 1969 to 2018 recording hourly water levels (University of Hawaii Sea Level Centre (UHSLC) 2019; Caldwell *et al* 2015) and monthly revised local reference (RLR) levels (Permanent Service for Mean Sea Level (PSMSL) 2019; Holgate *et al* 2013). From 1969 to 2018, mean sea level in Palau rose by around 11 cm (figure A1(a)) at 2.3 ± 0.4 mm yr^{-1}. However, closer inspection

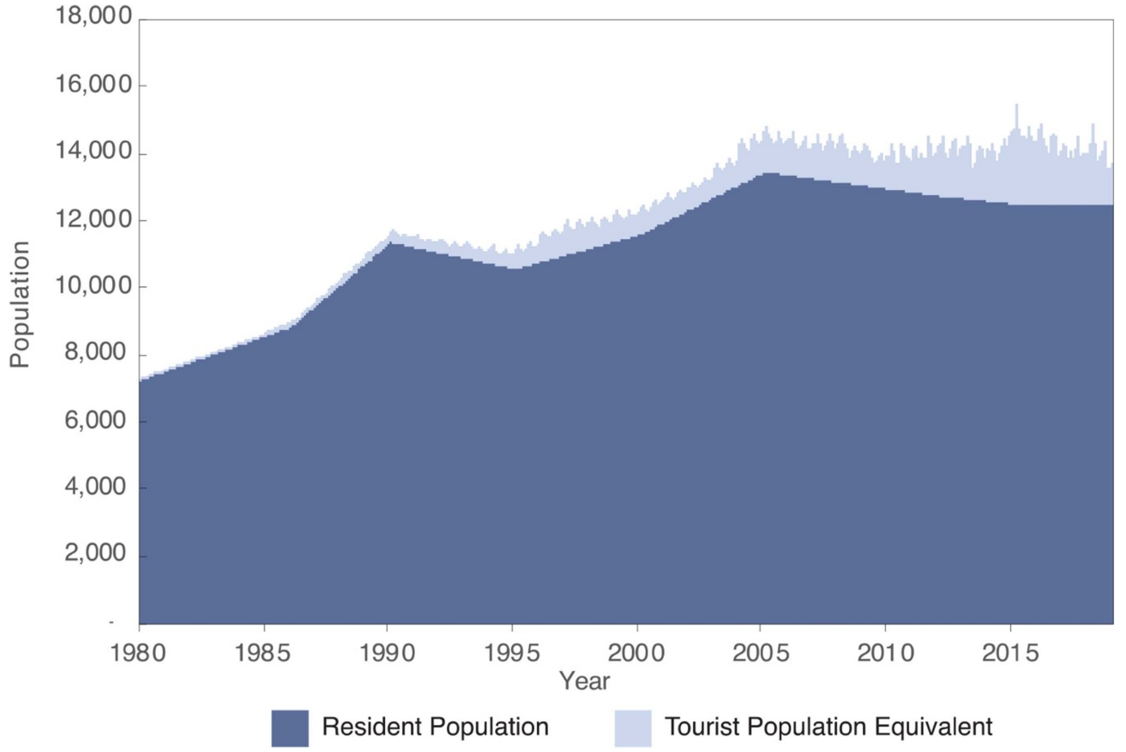

Figure 2. Monthly population estimate of public water users in Koror & Airai.

of the tide gauge record by estimating rates of change over a range of sliding windows (where minimum two-thirds data is available) reveals an increasing rate of sea level towards the present reaching 6.6 $\pm$ 1.0 mm yr^{-1} from 1991–2018 (see figure A1(b)), which is consistent with results at the global scale (Nerem *et al* 2018) though clearly amplified by local effects such a regional ocean thermal expansion and far-field contribution from northern hemisphere glaciers (Meyssignac *et al* 2017).

We evaluate whether vertical land motion (VLM) affects mean sea level in Palau by comparing satellite altimetry that measures geocentric sea level (also called absolute sea level, ASL) with the tide gauge record (measuring RSL), where VLM = ASL—RSL (Kuo *et al* 2004). Data showed that inferred local land motion at the tide gauge, and by extension the surrounding area including that of Koror is negligible over the last 25 years (see figure A2).

The monthly detrended tide gauge signal is anticorrelated with ENSO (-0.62, $p < 0.01$) over the full length of the record (see figure A1), while the magnitude increases significantly when assessing the correlation between decadal rate of sea-level change and decadal rate of ENSO (-0.88, $p < 0.01$). This indicates that multi-annual to decadal scale changes in RSL for Palau are strongly affected by ENSO, which is supported as a strong driver for Islands across the Western Pacific (Chowdhury *et al* 2007, Zhang and Church 2012).

To analyze exposure under future sea level rise, we used probabilistic regional sea-level projections (Jackson and Jevrejeva 2016) for RCP 8.5 (Moss *et al* 2010) extracted at Palau, using the mean of 27.7 cm for 2050, relative to 1986–2005. To align the sea level analysis with our GIS exposure analysis, where our baseline is the 1983 USGS topographic map, we added the mean sea-level rise from 1983 to 1995 of 2.5 cm estimated from Malakal B tide gauge to get a (Kopp *et al* 2014, Moss *et al* 2010) projected sea level rise of 30.2 cm in 2050 relative to 1983.

We use the hourly tide gauge water level record to estimate extreme water levels from annual maxima by first detrending all data by its relevant annual mean, then adjusting the series relative to the last 20 years (Wahl *et al* 2017). Following this, we select annual maxima for each year giving 49 values. We fit an extreme value distribution to the annual maxima (see figure A3) using maximum likelihood to estimate location and scales parameters assuming the shape parameter is zero (i.e. a Gumbel distribution, see for example Hunter *et al* 2017). Finally, we calculate the fitted distribution up to the 100-year flood event (see figure 3). Although criticism of the Gumbel distribution exists occurs in the literature as overestimating rare event water levels (Wahl *et al* 2017), here the distribution fits annual maxima in the 1 to 100-year event range with a root mean square error of 6.83 mm, which is supported by other extreme event analyses (Hunter *et al* 2017).

Extreme water levels between the 1- and 100-year event have a range of ∼27 cm (95 to 122 cm) where 17 cm of this difference occurs in the first 10-year return period interval. This relatively small range implies that small changes in the position of mean sea level will dramatically alter the magnitude of extreme water levels of across all return periods (Hunter 2012). Adding the 10-year return period (111.5 cm) to 1983 and 2018 mean sea level results in water levels of 111.5 cm and 124.5 cm respectively, which were rounded to 110 cm and 120 cm for exposure analysis. Adding the 10-year return period to the 2050 projected sea level rise (relative to 1983) gives a water level of 144 cm, which is rounded to 140 cm. We assume that there is no climate change induced shift in storm surge statistics (Kopp *et al* 2014).

2.3.2. Rainfall data

Historical rainfall data for Palau was downloaded from NOAA (National Climatic Data Center) and provides daily rainfall from 1980–2018, which was compiled into monthly bins from 1980–2018 to match the population data.

The data illustrates consistent seasonal variations (see figure 4). The dry season starts in February and lasts until April, followed by the rainy season from June to July (see table A1). The maximum annual rainfall, 5400 mm, and minimum annual rainfall, 2452 mm, for the 39-year period both occurred within the last 8 years, 2011 and 2015, respectively. These extremes are consistent with regional and global studies predicting increases in annual rainfall variation due to future climate change (Karnauskas *et al* 2016).

To project future rainfall, nine Couple Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al* 2012) climate models were used to create localized climate data specific to Palau (excluding the Southwest Islands) (see table A1). To refine these models, based on RCP 8.5 scenario, we use observed rainfall data from 1961–1990 as a control and bias-corrected the annual mean and variation of the models' outputs to more closely replicate the that rainfall data.

The three models that most accurately replicated the historical data in annual mean and variation (bc1m, hg2e and mc3) were applied to predict daily rainfall from 2041–2079. Hg2e was the most accurate in both mean rainfall and variance of rainfall when compared to observed data (see table A1). The three models projected mean annual rainfall reductions between 1.6–16.6% and increased annual variance between 0.3–3.4%. In all three models interannual variance also increased 3.9–7.4% causing unequal changes in average monthly rainfall as seen in the higher than average rainfall reductions during the dry season (see figure 4 and table A2). These models all illustrate that Palau can expect a significant rise in hazards greatly increasing future water shortage risk.

2.4. Separation of exposure and hazard

2.4.1. Coastal flooding

While 20th and early 21st century mean sea level rise has not visibly inundated the coastline of Koror, population growth resulted in the expansion of the urban footprint towards and into the mangroves and reefs that fringe the coast. We combine our tide gauge and GIS mapping analyses to determine whether sea level rise or urbanization was more significant in increasing coastal flooding risk. Due to the lack of sea level data at 1954, we only use that building data to show urban expansion.

We take the water levels derived from the mean sea level data and map them to contour layers in GIS for each year respectively. Buildings touching or lying below these elevations are considered to be exposed to the 1-in-10 year flood event at that time.

To separate coastal flooding impacts from urbanization and climate change we created an exposure matrix (see table 1). The baseline exposure (1) calculates the number of 1983 buildings exposed to a 1983 10-year flood event. Adding the rise in mean sea level at 2018 (2) and projected rise by 2050 (3) and calculating the additional exposed 1983 building shows how climate change hazards would have increased exposure if urbanization had not continued.

Current urbanization-induced exposure is determined by counting the number of buildings in 2018 that are exposed to the 1983 10-year flood event (4), as those buildings would have been exposed without climate change. Adding the rise in sea level at 2018 (5) and projected rise by 2050 (6) and counting the additional exposed buildings gives the exposure due to climate change-induced sea level rise.

2.4.2. Water shortage

Differences in data type and availability required a different approach for the water shortage analysis to separate the effects of urbanization and climate change on risk. The case study area was also expanded to include the entire urban area, Koror and Airai, because they use the same water source and together hold 78% of Palau's population virtually all of its tourism.

There are many studies analyzing the water shortage, however, these methods are not always appropriate or possible for PICs as river water is often not the main water source. Even though Palau uses surface water, stream flow data is not sufficient for the analysis period (U.S. Geological Survey 2016). Other methods to evaluate climate change's effects on water stress use drought indices (Edwards and

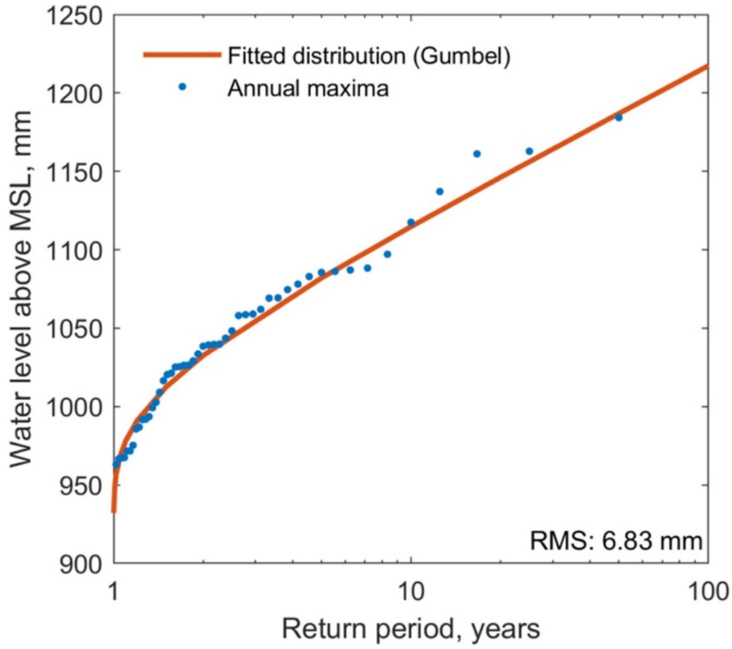

Figure 3. Water level return period for Malakal tide gauge hourly data (UHSLC).

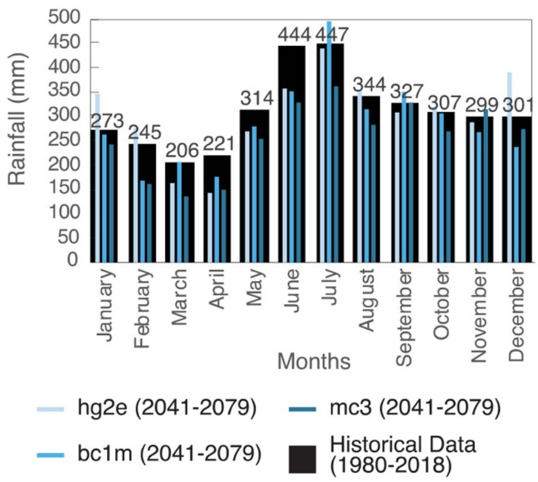

Figure 4. Average Monthly Rainfall from 1980–2018 (National Climatic Data Center), and projected rainfall from the three most accurate CMIP5 models (bc1m, hg2e and mc3) from 2041–2079.

Table 1. Coastal flooding exposure matrix.

	Buildings exposed at the 1983 sea level + 10-year flood (1.1 MASL)	Additional buildings exposed at the 2018 sea level + 10-year flood (1.2 MASL)	Additional buildings exposed at the 2050 sea level + 10-year flood (1.4 MASL)
1983 urbanization	1. Baseline exposure	2. Climate change-induced exposure (if urbanization stopped)	3. Future climate change-induced exposure (if urbanization stopped)
2018 urbanization	4. Current urbanization-induced exposure	5. Current climate change-induced exposure	6. Future climate change-induced exposure

Mckee 1997, Zagar *et al* 2011, Hanasaki *et al* 2013, Karnauskas *et al* 2016, WMO 2016). However, while studies in continents focus on the supply of water, PICs limited water sources are much more subject to demand side changes. Thus, based on these drought indices and the data available in the case study area, we consider supply and demand equally and use the change in precipitation and public water users to investigate water shortages in Palau's urban area.

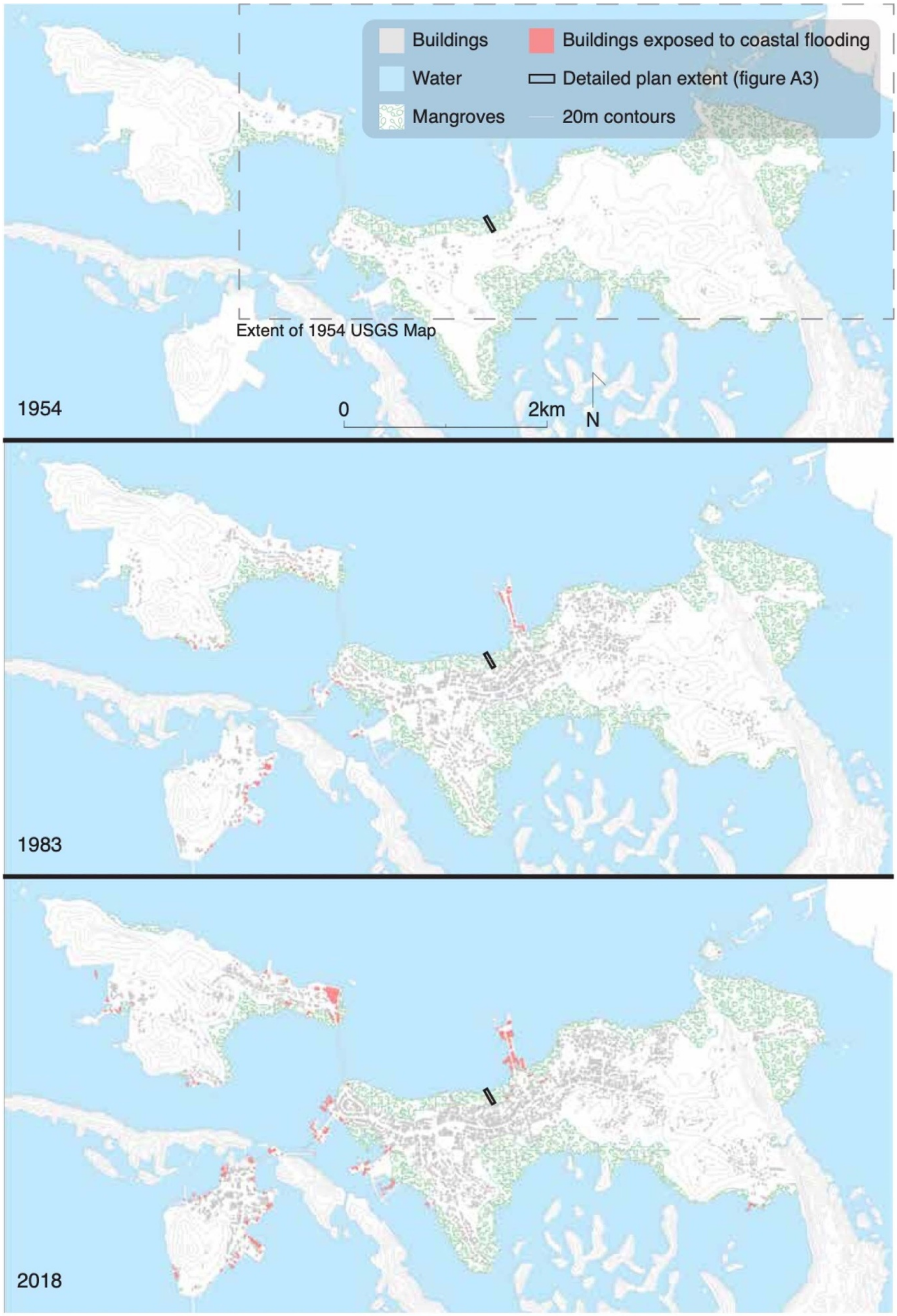

Figure 5. Maps showing urbanization in Koror from 1954–2018. Exposed buildings are based on that year's mean sea level plus the 10-year flood event.

To separate changes to rainfall and water demand we create a water scarcity index (WSI) dividing predicted demand, population growth dependent, by water supply, rainfall dependent, shown by the following equation:

$$\boldsymbol{WSI} = \frac{\Delta \textit{Predicted Monthly Water Demand}}{\Delta 5 \textit{ Month Average Rainfall}}. \quad (1)$$

This index enables us to manipulate population growth to simulate how urbanization contributed to the reported water shortages and estimate if these events would have happened in the absence of this urbanization.

We use per person water consumption estimated in 2007 (ADB). These rates will be multiplied by the number of tourists and residents and days in the respective month to calculate the predicted monthly water demand (PMWD), shown by the following equation:

$$\boldsymbol{PMWD} = d(xP_t + yP_r) \quad (2)$$

where d is the number of days in the given month, P_t is the population of tourists, P_r is the population of residents. The value of x and y represent the water use in liters person^{-1} d^{-1}, 1366 and 443 respectively (ADB 2007).

The water supply portion of the WSI uses millimeters and not liters because of obstacles in converting rainfall over the watershed to volume. The catchment area for the Ngerimel Dam is known and the yield can be roughly estimated (by simply multiplying the watershed area by rainfall), but it is supplemented by another river source via a pump and pipe, the yield of which cannot be estimated. Due to these complications, we simply used rainfall and treated the WSI as a unitless index.

The WSI estimates water scarcity, but to determine the level of water scarcity that triggers a water shortage we set a water shortage threshold (WST). To establish the WST, we reviewed historical records (government reports and newspapers, from 1992 when regular newspapers entered publication) in Palau and cataloged three major water shortage events (1983, 1998 and 2016) affecting water supply and agriculture across Palau and four minor ones (2002, 2005, 2010 and 2018) only affecting Koror between 1980–2018. We then set the WST so that the WSI most accurately replicated these events. To further calibrate the WSI, a 5-month moving average of monthly rainfall was chosen after testing averages ranging from 1–24 months because it most closely simulated actual water shortages.

The WSI successfully replicated 6 out of 7 of these water shortages and recorded 18 months above the WST, though it counts 2 water shortages for the major 2016 water shortage, which was only one event (see figure 6). The index failed to reproduce a minor water shortage that occurred in 2002, likely because it was between Census counts and the population may have grown more quickly than the assumed linear growth.

To determine how individual exposure and hazard components (past/present population and observed/projected rainfall) contributed to risk, we made a water shortage exposure matrix (see table 2). However, because this analysis involves time periods and not single, discrete years, instead of comparing all scenarios to a base year (like in the coastal flooding exposure matrix) this matrix shows the number of water shortage events and months above the WST for each scenario. Scenarios 1 establishes an estimated baseline exposure by simulating water shortage risk if the urban area population stopped growing after 1980, with actual tourist growth from 1980–2018, over the observed rainfall period (1980–2018). Scenario 2 projects future climate change-induced exposure by combining the 1980 population and 2015 tourist numbers (tourist arrivals will vary based on the month to mimic the tourist season) with the three future rainfall models. Scenario 3 demonstrates how urbanization increased exposure today by combining actual population/tourist growth and rainfall over the observed rainfall time period. Scenario 4 projects how future climate change-induced exposure will affect risk at present urbanization levels, using 2015 population and tourist arrivals (tourist arrivals will vary based on the month to mimic the tourist season). This will illustrate how urbanization and climate change independently and jointly affect water shortage risk.

3. Results

3.1. Coastal flooding

Koror's substantial post-WWII building growth (see figure 5) had large impacts on coastal flooding exposure. In 1983 a 10-year flood event exposed 79 buildings. By 2018, the same sea level and flood event exposed 207 buildings, more than doubling the exposure in 35 years. Three additional buildings from 1983 and 14 from 2018 were exposed by the same flood event at the 2018 sea level, meaning that sea level rise from 1983 to 2018 did not significantly increase hazards to coastal flooding. Adding the 2050 projected sea level rise to the flood event resulted in another three additional buildings from 1983 and eight from 2018 to be exposed, again showing that sea level rise is not as big a contributor to coastal flooding (see table 3).

Urban expansion in Koror caused 93.7% of coastal flooding exposure found in 2018. Future sea level rise still only exposes eight more buildings even though Palau is predicted experience above average global increases. This is due to Palau's relatively

Table 2. Water shortage analysis matrix.

	1980–2018 observed rainfall	2041–2079 projected rainfall: bc1m	hg2e	mc3
1980 urbanization	1. Baseline exposure	2. Future climate change-induced exposure		
2018 urbanization	3. Urbanization-induced exposure	4. Combined future exposure		

Table 3. Coastal flooding risk matrix results.

		Buildings exposed at the 1983 sea level + 10-year flood (1.1 MASL)	Additional buildings exposed at the 2018 sea level + 10-year flood (1.2 MASL)	Additional buildings exposed at the 2050 sea level + 10-year flood (1.4 MASL)
1983 urbanization	Exposed buildings	79	3	3
	% of all buildings	5.01%	0.19%	0.19%
2018 urbanization	Exposed buildings	207	14	8
	% of all buildings	6.43%	0.43%	0.25%

steeper geography along the coastlines, which acts as a shield slowing sea level rise's incursions inland and shows that urbanization exposure will continue to have a disproportionate influence on coastal flooding risk in the future (see figure A4).

3.2. Water shortage

The baseline exposure resulted in three water shortage events, the same years as major recorded events, and 6 months above the WST (see table 4). Adding urbanization-induced exposure doubled the number of water shortage events, the same years as three of the minor recorded events, and tripled number of months above the WST (see figure 6). These findings suggest that not only did urbanization cause the three minor events after 2000, but also increased the severity of what may have been minor events, illustrating how population growth within a small water supply system can have significant consequences.

Using the three projected rainfall models, changes to climate change-induced exposure ranged from decreases in both water shortage events, 2, and months above the WST, 2, to large increases, 13 and 38, respectively, using 1980 urbanization levels (see table 4). This illustrates uncertainty in estimating future rainfall. However, when combining projected rainfall with 2018 urbanization levels all three rainfall models predicted significant increases in water shortage risk. The most optimistic model, hg2e, still estimated 18 water shortage events and 39 months above the WST, more than doubling the number of observed events (see table 4 and figure A5). This does not even account for potential urban growth that economists and statisticians project (EconMAP 2019) and is likely to occur as new hotels in Koror are being constructed today.

4. Discussion

4.1. Urbanization exposure: coastal flooding

Historical maps demonstrated urban expansion towards the coastline and eventually past it in certain areas reflecting a commonality with other PICs. As people moved to Palau's sole economic center and former capital, Koror State Government leased state land for people to build their homes. As growth continued and land became scarce the State began leasing out areas of mangrove providing reimbursement to leasers for filling the land, essentially subsidizing coastal development. This development pattern exposed 6.4% of all buildings to coastal flooding. By 2018, the rise in mean sea level only increased exposure half a percent and 2050 sea level projections added a further quarter of a percent, though in both cases (due to mapping resolution) water levels were rounded down by 1 and 4 cm potentially leading to a small underestimation (see section 2.3.1). Given the deep uncertainty associated with mean sea level projections, particularly in the second half of this century but discernible by 2050, future sea level rise will continue to increase exposure in the long term. For example, if mean sea level rise in Palau were to instead double by 2050 (53 cm relative to 1983, 95th percentile RCP 8.5, Jackson and Jevrejeva 2016), present-day exposure would increase significantly more to 30%. Overall though, these results confirm urbanization's disproportionate effect on coastal flooding risk.

However, buildings we determined to be exposed may vary in the frequency and severity to which they are actually affected by coastal flooding today. As long term mean sea level rises the number of affected buildings will continue to increase as well. Shorter term ENSO-dependent sea level variations will also have great effects on whether and how frequently exposed buildings are affected by

Table 4. Water shortage risk matrix results.

		1980–2018 observed rainfall	2041–2079 projected rainfall		
			bc1m	hg2e	mc3
1980 urbanization	Water shortage events	3	2	4	13
	Months above the WST	6	2	8	38
2018 urbanization	Water shortage events	6	19	18	23
	Months above the WST	18	64	39	88

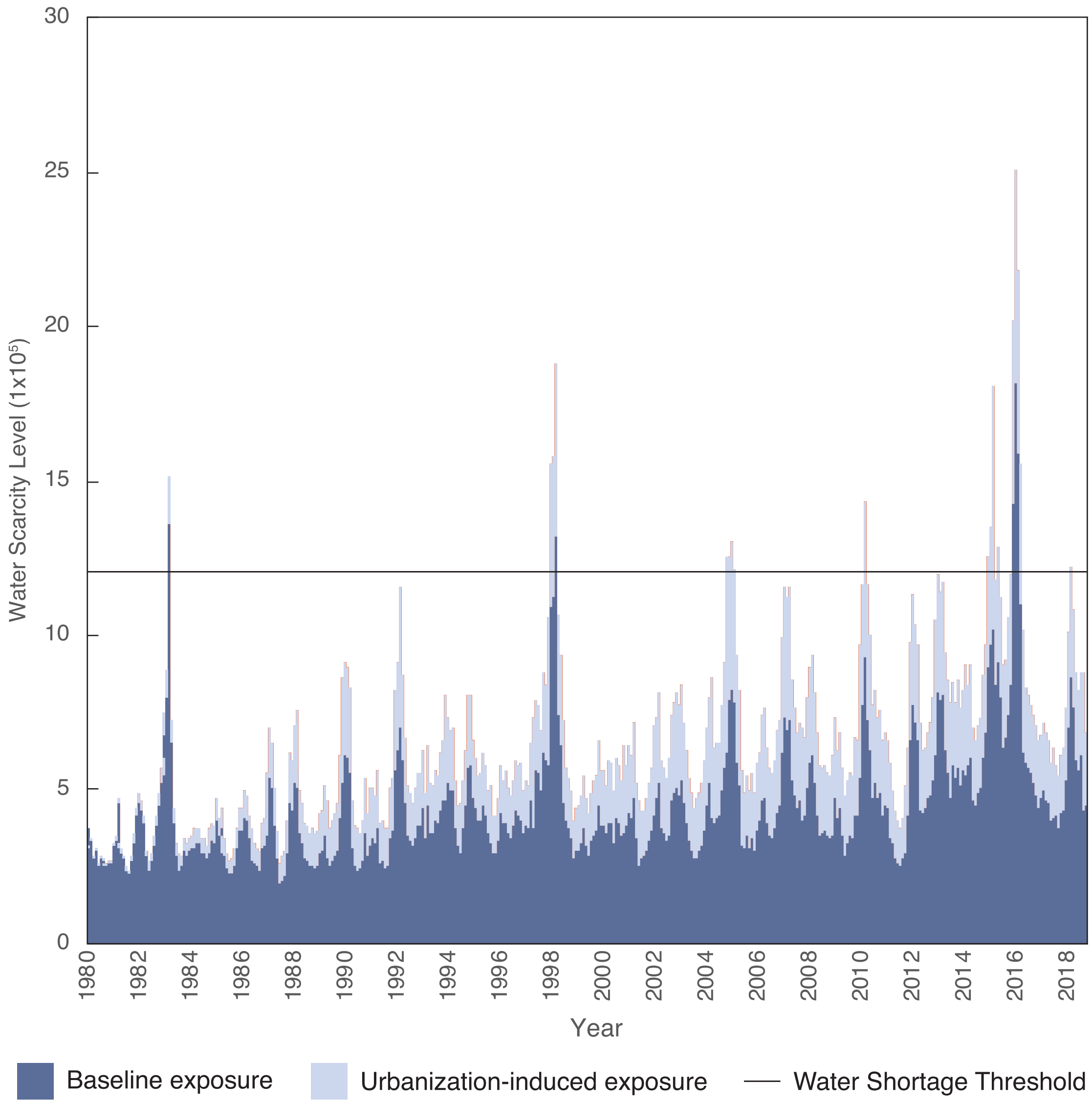

Figure 6. Water shortage index shows urbanization's impact on water scarcity (Actual WSI) and predicted WSI had growth not occurred (1980 Public Water Users WSI), 1980–2018

coastal flooding (e.g. Chowdhury and Chu 2015, Han *et al* 2017).

Furthermore, while Koror's volcanic and limestone lithology is prevalent across other PICs, there are many atoll islands (including other states in Palau) that are much more exposed to changes in sea level. For example, like the Marshall Islands are a much lower mean altitude and flatter, meaning that even more minor increases in sea level over the 20th century will have increased exposure more relative to urbanization than we found in Koror.

4.2. Urbanization exposure: water shortage

While the population of Palau grew, its number of public water users grew with increasing tourism, and policies aimed at increasing access to running water as a means to increase quality of life were implemented (ADB 2013). Reliance on the newly expanded water supply infrastructure came at the expense of formerly common rainwater catchment systems and their use dropped dramatically from 48% in 2000 to only 5% by 2015 (Republic of Palau (ROP) 2015). Our analysis showed this urbanization likely caused three water shortages and an additional extra 12 months above the WST, increasing the severity of the water shortages that may have occurred regardless. Our future rainfall projections exhibited the possibility of reducing water shortage events to two at 1980 urbanization levels. However, with the current population major increases to water shortage events and their severity that resulted in anywhere from 18 to 23 water shortage events at two to four times the severity at present population levels. Based on these findings it is evident that urbanization in Palau played a major role in water shortage risk over the past several decades and both urbanization and climate change have the potential to equally impact future water shortage risk.

Though Koror and Airai's water reservoir satisfies the populations' demand most of the time, the increased water use makes it more susceptible to ENSO-induced rainfall variations already occurring (Power *et al* 2017, Wang *et al* 2017). Understanding these variations are just as important for planning how to manage water resources as estimating long-term rainfall changes.

PICs that raise demand on freshwater resources immediately adjacent to swelling urban populations may also exhibit increased exposure to rainfall variations. As Palau has one of the highest urbanization rates in the increasingly urban Pacific (Asian Development Bank (ADB) 2016), other PICs that are not currently experiencing the same water shortage issues as Palau may see their future in Palau's current situation. Even if urbanization does not increase as predicted, future short and long term rainfall variations may push their water supply limits to the point where they too cannot reliably produce water when faced with more frequent and severe droughts.

4.3. Pathways to lower risk in PICs

Growing climate risk research in PICs has reframed the conversation to not only understand long-term changes in climate, but also short term climate variations and how human activity produces local impacts (e.g. Chowdhury and Chu 2015, Han *et al* 2017, Power *et al* 2017, Wang *et al* 2017). Fortunately, this bolsters the toolbox from which PICs can address climate risk. They can track and respond to seasonal sea level and rainfall variations and, as this research found, manage urban development, all while continuing to demand carbon emission reductions in international forums.

Our correlation analysis concurred with other studies that PICs are particularly susceptible to shorter time scale elevated sea levels during La Niña years (Chowdhury and Chu 2015, Han *et al* 2017). The results of this research also demonstrated PICs exposure to rainfall variations created by the same phenomenon. In fact, until January 2020, the Pacific ENSO Applications Climate Services (PEAC) provided seasonal sea level and rainfall forecasts to US Associate Pacific Islands allowing them (in theory at least) to make temporary coastal management and water usage plans at this timescale (www.weather.gov/peac/sealevel). For sea level, the empirical correlation-based model provided high skill scores when combining zonal wind fluctuations to sea-surface temperature to drive seasonal forecasts (Chowdhury *et al* 2015), however these did not incorporate long term projections of mean sea level, nor evaluate exposure as we have performed here.

Utilizing these relationships to inform near-term sea level and rainfall projections would allow PICs to implement temporary protection measures in a timely fashion that can lead to long term solutions. After first identifying coastal exposure to short term (2–3 years) elevated sea level, governments could decide those areas to protect, whilst incentivizing land-owners/tenants in those areas or other areas with high long term exposure to move with buyouts of land combined with infrastructure support (residential, electricity, water and transportation) of inland development areas. Those development areas could utilize different water sources to reduce pressure on urban water supplies while urban homes utilize tools such as rainwater harvesting and use of saltwater for toilets. This should be tempered by the point that further seaward development will erode the natural flood protection provided by the mangroves, and place further stress upon currently limited water resources.

However, PICs are a diverse group of island lithologies and in a atoll nation such as the Marshall Islands moving residents from the lowest lying sand atolls to higher islands may help against coastal flooding only to increase water shortage risk in those areas. There are other complexities that must be taken into account, such as the use of groundwater and land subsidence (Erban *et al* 2014), and the fact that PICs may need international support to implement these adaptation strategies. While an uncertain climate future still promises major changes (Church 2006, Becker 2012, Power *et al* 2017, Wang *et al* 2017), there is a growing range of options for PICs to reduce future climate risk through tracking short term climate variations, urban management, all while they continue lobbying for carbon emission reductions.

4.4. Limitations and future research

Research in PICs is difficult due to data availability and though we were able to find usable data in Palau there are still some factors on which to improve. More accurate and precise DEM data could better estimate coastal flooding exposure in Koror. The USGS data used was created in 1983 and is both not precise and does not account landscape changes that occurred. However, with the limited data available the significant coastal flooding results leads us to think that more accurate DEM data will show similar results.

Similarly, the WSI could be improved with a more accurate estimate of water supply instead of simply using rainfall. However, without historical data on dam levels, rainfall data was sufficient to accurately replicate water shortage events. It is more likely that the five years between population counts contributed to inaccuracy more on the demand side than rainfall on the supply side. Even with these shortcomings, we believe the results still clearly show urbanization had a substantial effect on climate risks, which is often overlooked in Pacific research.

Both coastal flooding and water shortage risk analyses would be made more complete with a study of vulnerability to complete the risk equation. Vulnerability is traditionally low in PICs due to strong social and community ties, which foster strong resilience in the face of naturally occurring and anthropogenic environmental changes (e.g. Firth 1959, Rappaport 1963, Lessa 1964, Marshall 1979, Campbell 1990). Throughout the course of research for this paper, surveys and interviews with residents in Koror found they remained resilient to increased risk as people relied on both soft solutions through social and community bonds and hard solutions like filling their own land or using water storage tanks. This resiliency is common to the Pacific and is a vital to maintain and enhance as climate change alters hazards (Barnett 2001).

Future research would do well to combine seasonal variations like those in PEAC, long term trends and exposure analysis to look at other urban areas in the Pacific with different lithologies, population and per capita GDP. Palau serves as a good example for Post-WWII urbanization, however, research into other islands may come to different conclusions based on these factors. Even if the results are the same, differing circumstances such as availability of alternative water sources may require different solutions. The development of a strategic adaptation framework embedding analyses of the type presented here with a consistent, repeatable methodology would allow PICs to tailor solutions to their people and islands.

5. Conclusion

We attempted to disentangle the effects of climate change and urbanization on coastal flooding and water shortage risk in Palau and the Pacific, adding to the growing body of literature examining all components of risk in PICs (e.g. White and Falkland 2010, Forbes et al 2013, Kumar and Taylor 2015, Kench et al 2018, Kelman 2019) . At present, coastward urbanization (into mangrove and reef) and population growth have dominated the increase in coastal exposure and reduced water resilience respectively. Therefore, the future coastal stability of Koror requires coastal management encompassing sensitive urban development and preservation of its vital coastal ecosystem (Forbes et al 2013). Furthermore, improvements to the internal management of water resources in Palau's urban area will strongly improve water resilience in response to public demand and the likely increases in rainfall variability (White and Falkland 2010, Kelman 2019).

We have shown in this study the importance of continued observations drawn from *in-situ* measurements, geospatial mapping, and climate modelling to understand the factors governing urban exposure to environmental change. This objective approach informs a range of stakeholders from governments, private developers and individual homeowners. While continuing to advocate for strong emission reduction targets on the international level, PICs would do well develop procedures to track short-term sea level and rainfall variations (like PEAC) and implement policies which facilitate short term risk-minimizing actions that can evolve into long term solutions that ensure proper coastline and water supply management to lower exposure to coastal flooding and water shortage risks.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Numbers JP18H03417 and JP26870164 and funded by the Collaborative Research Project of Research Institute for Islands and Sustainability, University of the Ryukyus and the Robertson Foundation for Climate Econometrics Grant Numbers 9907422 and 9908921. The authors are grateful to our partners in Palau who helped improve this research, Erbai Matsutaro, Chris Kitalong and the students at the Pacific Academic Institute of Research.

Competing Interests

The authors declare no competing financial interests.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix

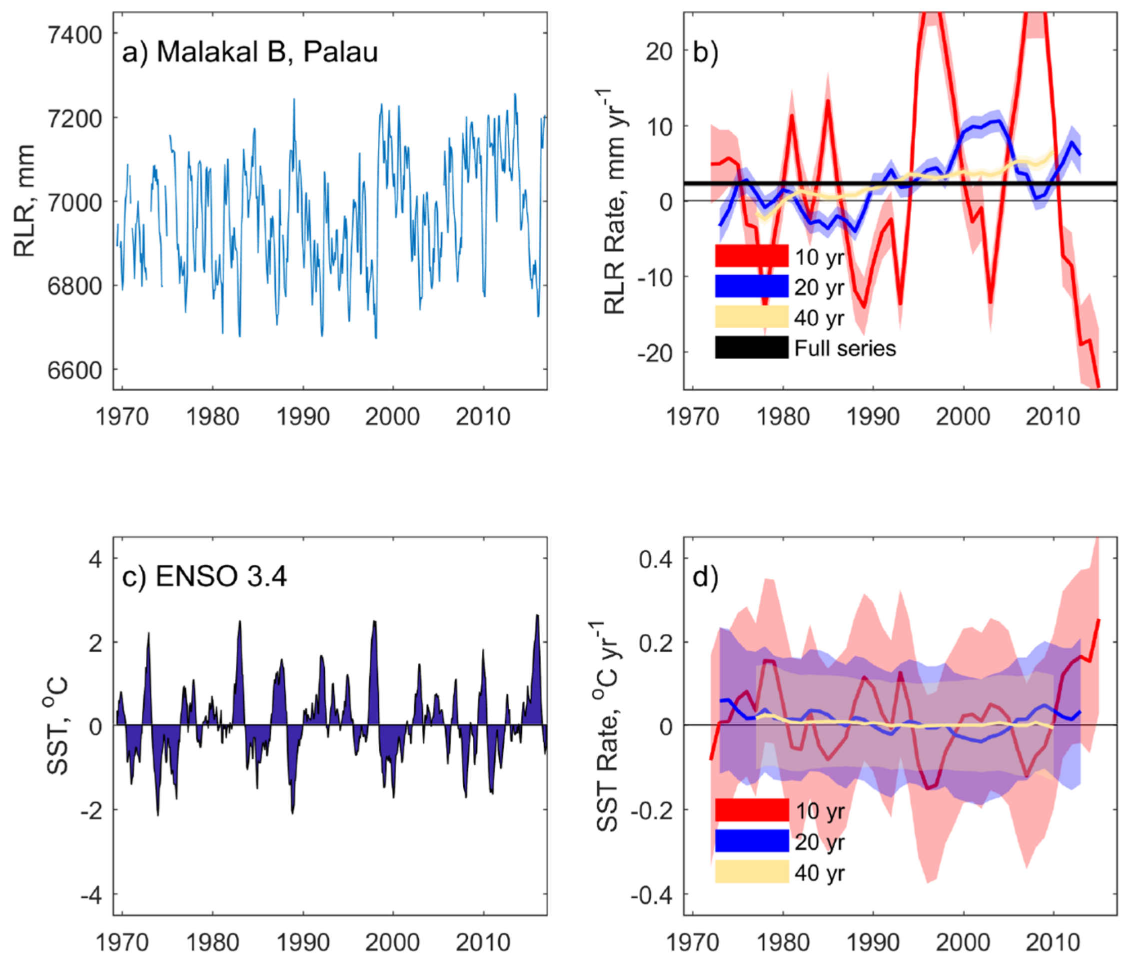

Figure A1. (a) Malakal B tide gauge record monthly observations (PSMSL). (b) Rate of RSL for different sliding window lengths. (c) ENSO 3.4 Index. (d) Rate of change of sea-surface temperature (SST) for range of sliding window lengths.

Table A1. Climate model accuracy in replicating historical rainfall data, 1961–1990 (*models chosen for future analysis). Coefficient of variation shows the difference in historical annual variation and model annual variation. Mean sums the absolute difference between historical average monthly rainfall and model average monthly rainfall for each month in a calendar year to account for seasonal variations in rainfall while comparing average annual mean rainfall.

Climate Model		Accuracy	
	Abbreviation	Coefficient of Variation	Mean (mm)
BCC-CSM1.1(m)	bc1m*	0.039	529.1
CNRM-CM5	cc5	0.040	529.6
CanESM2	ce2	0.023	531.6
CSIRO-Mk3.6.0	cs36	0.214	530.6
GFDL-ESM2M	ge2m	0.086	529.4
HadGEM2-ES	hg2e*	0.005	516.4
IPSL-CM5A-LR	ic5l	0.146	529.4
MIROC5	m50	0.055	529.6
MRI-CGCM3	mc3*	0.013	529.7

Table A2. Past rainfall and future rainfall projections summary.

	Historical (1980–2018)	bc1m (2041–2079)	hg2e (2041–2079)	mc3 (2041–2079)
Mean Annual Rainfall	3728	3426	3667	3111
Maximum Annual Rainfall	5483	5215	5792	3995
Minimum Annual Rainfall	2452	2169	2706	2131
Annual Rainfall Variance	16.7%	18.3%	20.1%	17.1%
Dry Season Mean Monthly Rainfall	224	184	194	149
Rainy Season Mean Monthly Rainfall	446	425	400	346

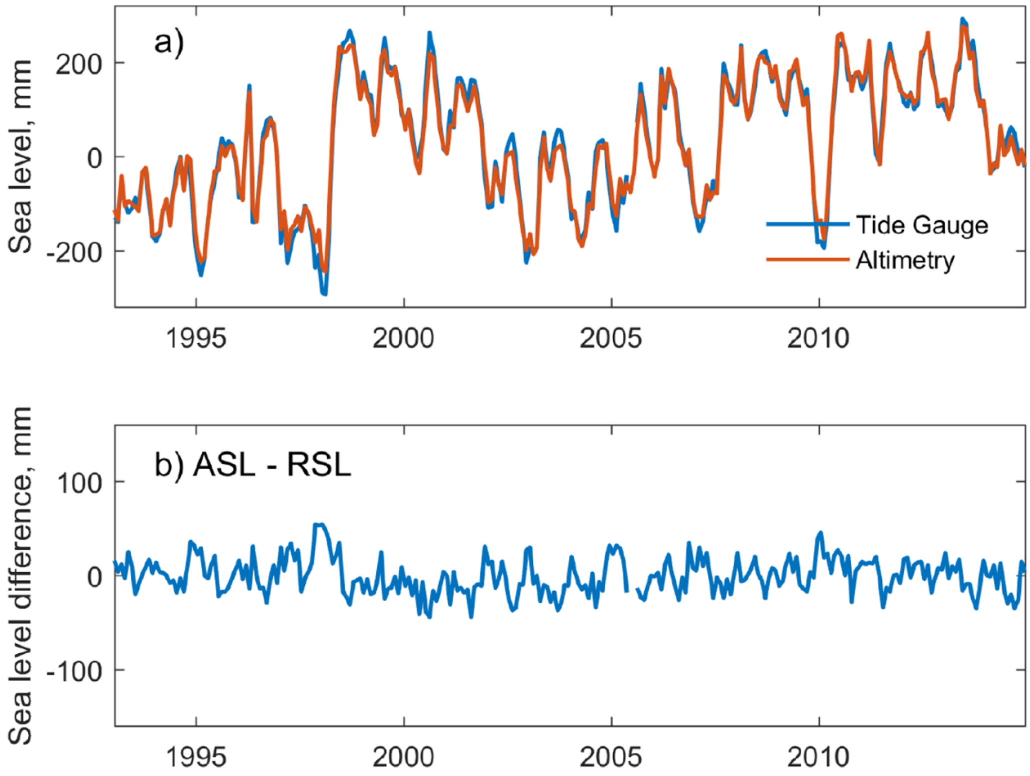

Figure A2. (a) Altimetry (AVISO) and Tide gauge (Malakal B, PSMSL) records for Palau. (b) Altimetry minus Tide gauge records over same period to infer vertical land motion.

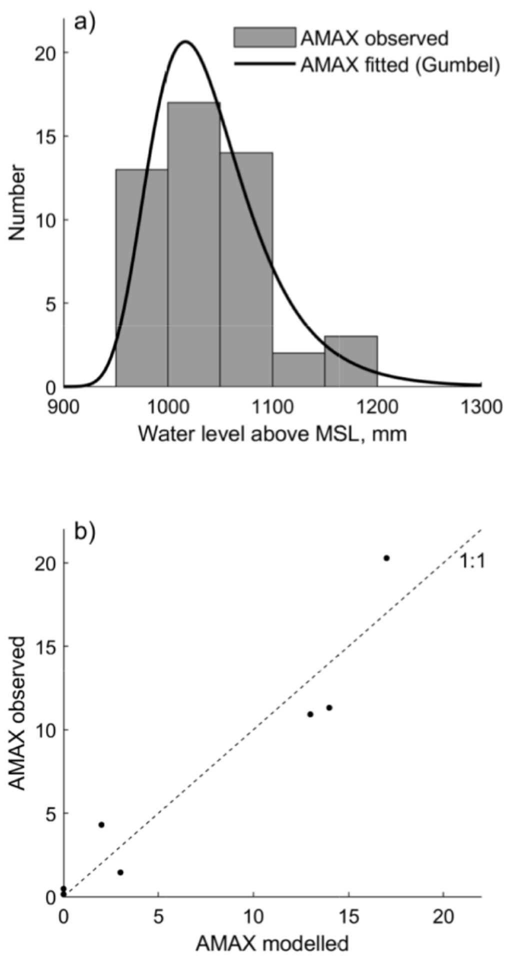

Figure A3. Extreme value distribution of annual sea level maxima.

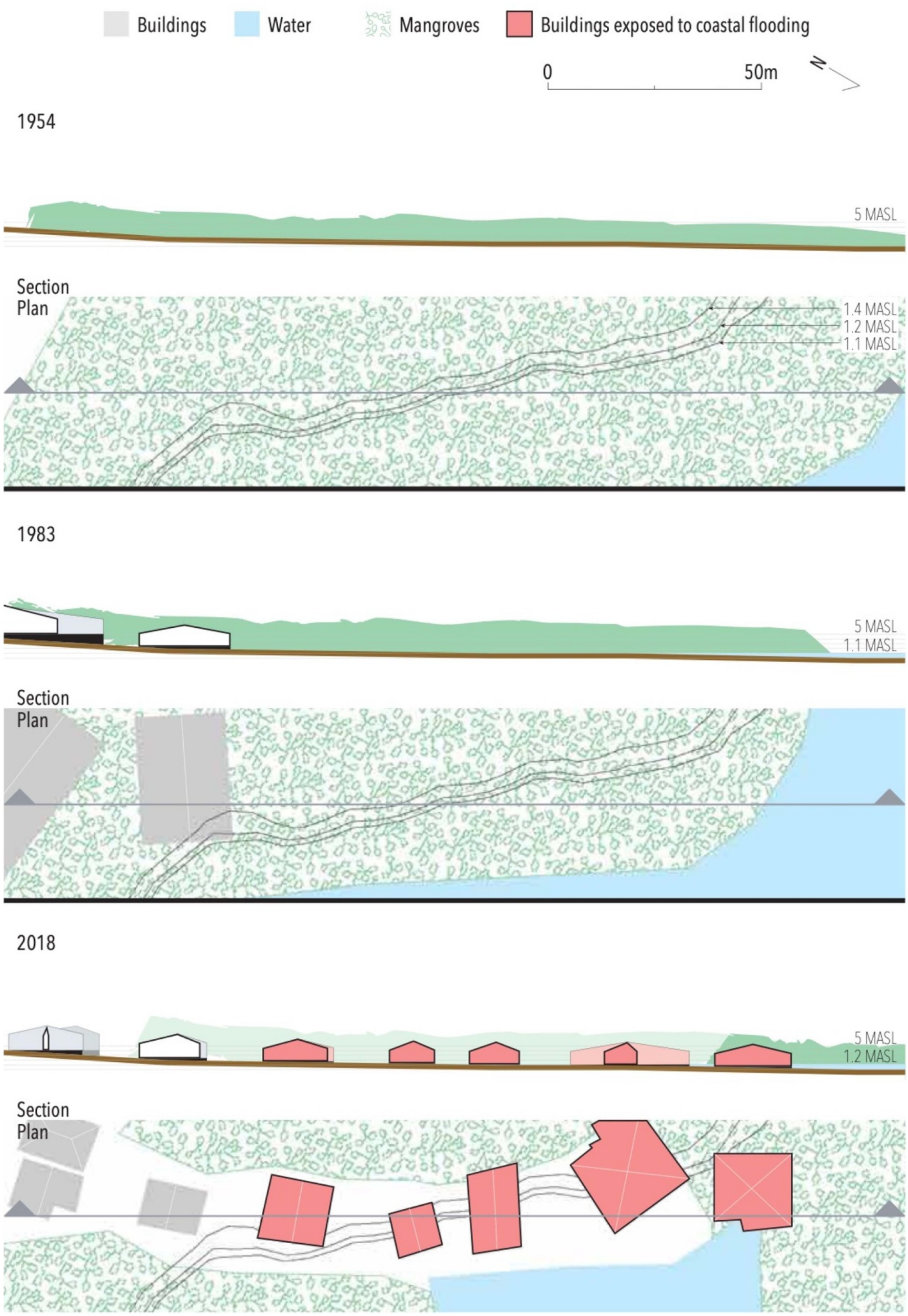

Figure A4. Map of coastal flooding exposure in Koror, Palau.

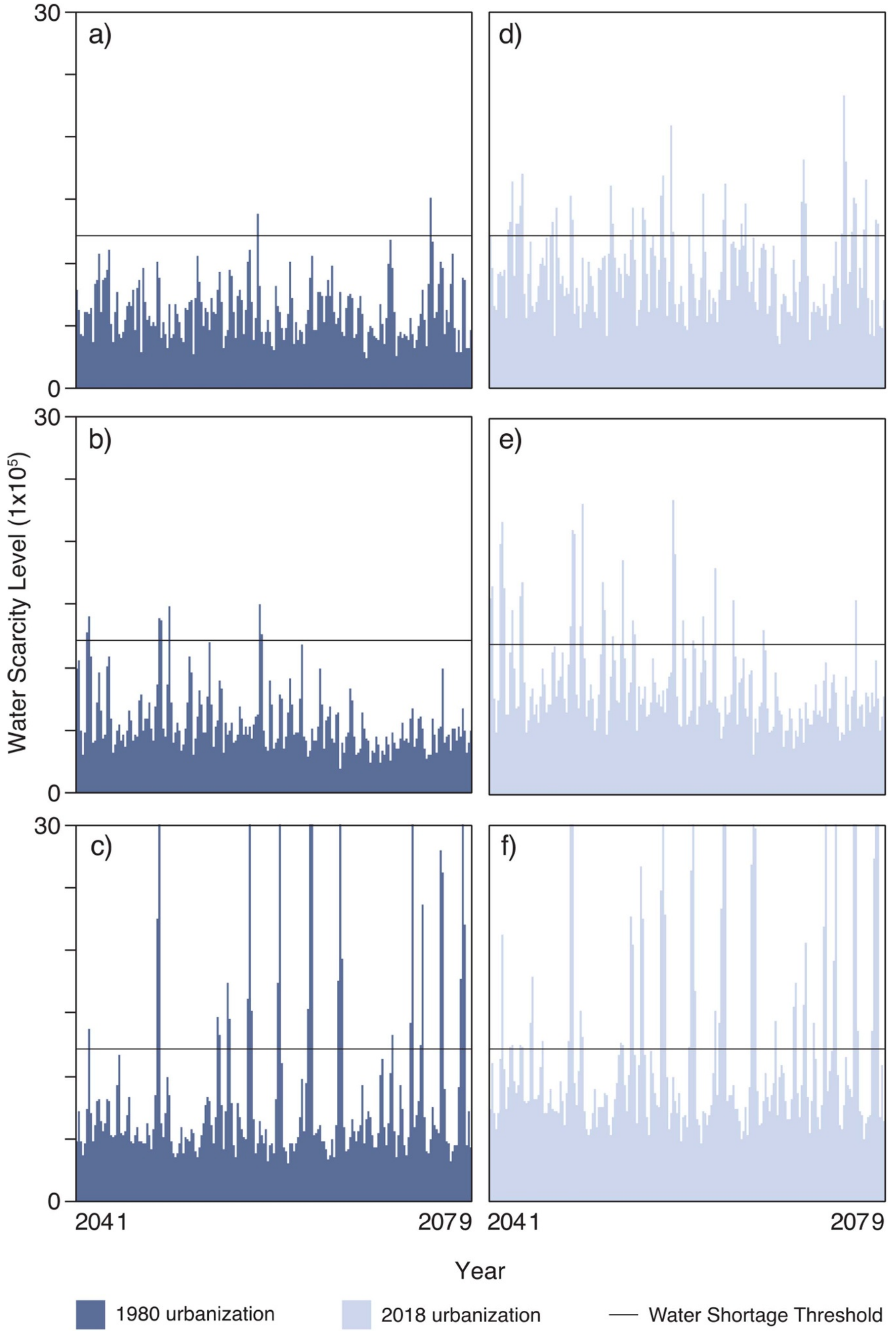

Figure A5. Future WSI, 2041-2079. Subfigures a, b and c show the WSI for scenario 3 using 1980 urbanization levels and future rainfall a) bc1m b) hg2e c) mc3. Subfigures d, e and f show the WSI for scenario 4 using 2015 urbanization levels and future rainfall d) bc1m e) hg2e f) mc3.

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